38.3: Predicting Color Breakup on Field-Sequential Displays: Part 2

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Abstract

We measured color-breakup thresholds for a simple field-sequential color stimulus while varying its luminance, contrast, and retinal velocity. Data analysis yielded an equation that predicts whether color breakup will be visible for specified viewing conditions. We compare this equation with an earlier version and discuss its uses and limitations.

Introduction

Field-sequential color (FSC) displays are attractive for head-mounted and projection applications because they have a resolution advantage over conventional color displays that is particularly useful when the display must be small. They are prone to the image-quality problem called *color breakup*, though, when run at the usual 180-Hz field rate. Unfortunately, the conditions under which 180 Hz is satisfactory are largely unknown. More importantly, the ways in which viewing parameters such as image contrast, retinal velocity, and adapting luminance affect field-rate requirements have not been established very well.

Arend, Lubin, Gille, & Larimer [1] used known spatiotemporal properties of the human visual system's luminance coding mechanism to predict the visibility of color breakup for a 180-Hz FSC display in terms of JNDs. They obtained a value of roughly 3 JNDs, which implies that breakup should be readily visible.

Post, Monnier, & Calhoun [2] measured field rates that produced threshold color-breakup detection for an FSC target over a wide range of viewing conditions. After averaging the thresholds across participants, we found that 97% of the variance was accounted for by

$$R = 66.6L^{0.10}M^{1.26}V^{0.52}, \qquad (1)$$

where L is the target's luminance in cd/m^2, M is its luminance modulation, V is its retinal velocity in degrees/s, and R is the threshold field rate in fields/s. Our apparatus superimposed the FSC target on the background, however, so the target and background summed spatially to produce a color mixture. As a result, changing the target's luminance contrast also changed the excitation purity of the RGB fields constituting it and may have affected the visibility of the color breakup. Usually, though, stimuli on FSC displays replace their backgrounds instead of summing with them, so this aspect of the experiment was a confound that should not occur in practical cases. The present experiment avoided this confound by changing the hardware configuration.

Method

Participants

The participants consisted of the four present authors, plus two volunteers. Their ages ranged from 28 to 50 years. They were screened for 20/20 near and far Snellen acuity (corrected or uncorrected) and normal color vision. The participants served in pilot studies before formal data collection began and therefore had substantial practice with the apparatus and stable criteria for judging the presence or absence of color breakup. Furthermore, all participants except AN took part in the Post et al. [2] study.

Apparatus

The apparatus (see Figure 1) consisted of a monocular Maxwellian-view optical system and used a rotating filter wheel to produce an FSC target on a uniform background at field rates up to 6 kHz. The target subtended 4 arc-minutes x 2 degrees visually (H x V) and moved horizontally at constant velocity through a 10-degree field of view, pausing briefly after each sweep. The apparatus was configured so the target did not sum with the background; otherwise, it was similar with apparatus that is described in more detail in [2].

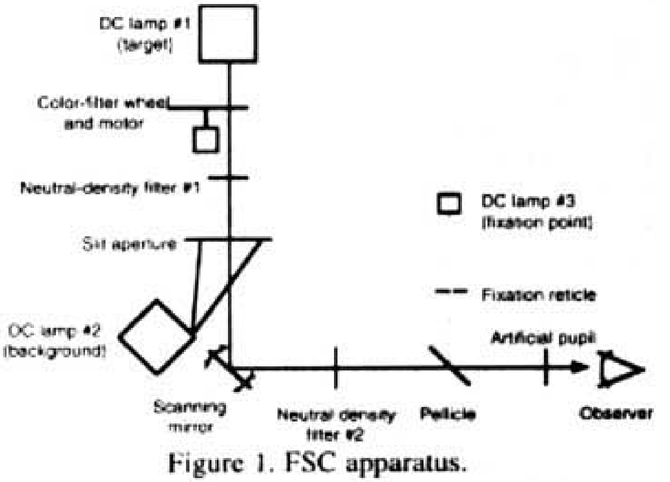

Figure 1. FSC apparatus.

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The CIE chromaticity coordinates of the RGB fields (see Figure 2) were chosen to match the RGB primaries of a typical color CRT. The fields were isoluminant; therefore, the color produced when the filter wheel spun was a purplish white, having the chromaticity coordinates shown in Figure 2. The background (also represented in Figure 2) was a slightly greenish white due to the presence of ultraviolet and infrared filters. Details of the calibration procedure are given in [2].

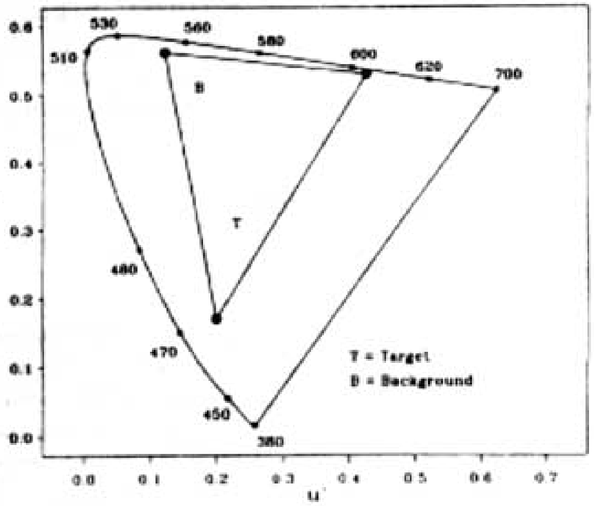

Figure 2. CIE 1976 uniform chromaticity-scale diagram showing the chromaticity coordinates of the FSC system's RGB primaries, the target, and the background.

Procedure

The experimental design was completely within-subjects with two replications. It consisted of five levels of background luminance (0, 5, 49, 468, and 2223 cd/m^2), five levels of target luminance modulation (0.47, 0.56, 0.66, 0.80 and 0.96), and four retinal target-velocities (6, 34, 85, and 200 degrees/s). We could not achieve 0.96 luminance modulation against the 2223-cd/m^2 background; otherwise, the design was a full factorial. In addition, target luminances of 28, 63, 218, 258, and 2216 cd/m^2 were tested against the black background at all four retinal velocities.

Trials cycled first through the retinal velocities, then the target modulations, and finally the background luminances, starting at the lowest values in each case. Thus, background luminance varied the least often and the participant's level of light adaptation was stabilized. Typically, the participants completed two or three background luminances in a 1- to 1.5-hour session.

For each trial, the participant foveated a central fixation point, observed sweeps of the target, and adjusted the filter-wheel's rotational velocity until color breakup in the target was just invisible. Next, the participant set the velocity to a higher, random setting and then adjusted it until color breakup was just visible. The average of the two velocities was taken as the participant's threshold for that trial and converted to the equivalent field rate in fields/s. Under some viewing conditions, the participant was unable to see the stimulus sufficiently to produce a setting; in these cases, the condition was skipped.

The target's appearance when it was moving is illustrated in Figure 3. The figure is meant to show that visual persistence caused the moving target to paint an image that resembled a chromatic grating. At the lower retinal velocities, luminances, and contrasts, the grating was narrow (i.e., contained only a few bars) and moved from one side to the other. As velocity, luminance, and contrast increased, the grating became wider. In the limit, the grating occupied the full field of view and appeared to be presented in brief flashes having a duration dictated by the velocity of each retinal sweep. In all cases, adjustment of the filter wheel's velocity altered the grating's spatial frequency. Thus, the detection of color breakup in this task was equivalent with the detection of chromatic modulation in a grating, and the participant's task consisted of adjusting the field rate until chromatic modulation was either just below threshold (yielding a monochrome stimulus) or just above threshold (yielding a faintly multi-colored grating). The participants were told to ignore any luminance modulation they might see and make their settings strictly according to chromatic differences.

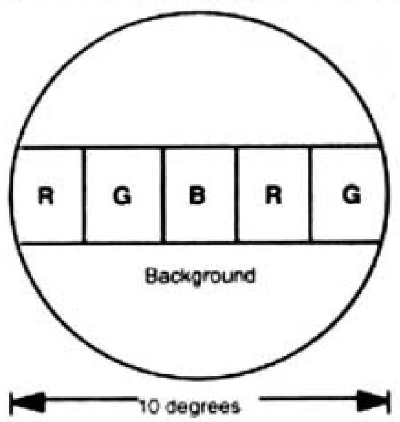

Figure 3. Target's appearance when $R/(3V)$ = 0.17 cycles/degree and the target moved left-to-right. Right-to-left motion reversed the order of the RGB fields.

Results

The data were averaged over participants, and conditions for which one or more participants were unable to set a threshold were deleted to avoid biasing the results. The mean for the highest target luminance (2216 cd/m^2) at unity modulation and 200 degrees/s was deleted also because it was clearly anomalous (see Figure 4), so retaining it would have degraded our ability to fit the rest of the data. We were left with a data set containing 53 means.

Nonlinear regression was used to find the best-fitting coefficients for an equation of the same form as Equation 1, using the Statistical Analysis System's NLIN procedure. The program converged quickly to the same solution from widely varying starting locations and yielded

$$R = 36.3L^{0.39}M^{1.06}V^{0.69}. \tag{2}$$

Equation 2 accounts for 95% of the variance, which implies that it gives a fairly good fit to the means, and all the terms are significant statistically, $p < 0.05$ in each case. Figure 4 summarizes our results: it shows, for all viewing conditions, each participant's mean threshold and the predictions from Equations 1 and 2.

We compared the coefficients in Equations 1 and 2 using t-tests and the Satterthwaite approximation for degrees of freedom [3]. The results show that the exponents for L and M do not differ reliably across experiments ($p = 0.11$ and 0.55, respectively), but the exponent for V and the scaling constant do ($p < 0.003$ in both cases). Equation 1 accounts for 89% of the variance in the present experiment's means; Equation 2 accounts for 91% of the variance in the Post et al. [2] means.

Discussion

The results from the regression analyses surprised us. We expected that decoupling the target's luminance contrast from its excitation purity would produce a smaller exponent for M in Equation 2 than in Equation 1 and leave the other regression coefficients essentially unchanged. We found, however, that the exponent for M in Equation 2 is smaller, but the difference is not reliable statistically, whereas other differences are. We also expected that Equation 1 would not predict our new data very well and Equation 2 would not predict our old data very well. Obviously, though, the cross-experimental predictions are quite good, despite significant differences (that do not appear where they were expected) in coefficients. Figure 4 shows the reason: Over the ranges of viewing conditions we explored, the equations yield very similar predictions.

Those who wish to use Equations 1 or 2 should be cautioned that extrapolating beyond the range of viewing conditions for which we have reported data can yield unrealistically high predictions. For example, for the condition involving 5 cd/m^2 background luminance, 0.47 modulation, and 200 degrees/s, Equation 2 predicts that a 759-Hz field rate is needed to prevent color breakup. However, none of our participants were able to establish a threshold for this condition (note that Figure 4 shows no data for this case). Therefore, in practice, the field rate for this viewing condition is immaterial.

We would like to develop a more general model that predicts the points at which the stimulus can no longer be seen and, therefore, the field rate is irrelevant. Preliminary exploration of this idea and comparison of the results against published data on spatial chromatic-modulation thresholds indicate that this goal is achievable. We would also like to check to see whether data for cases where the eye moves and the target is stationary are equivalent with the moving-target + stationary-eye cases we have studied thus far. In the meantime, though, Equations 1 and 2 provide the best tools available currently for predicting color breakup.

Acknowledgments

The work described in this article was supported by the Air Force Office of Scientific Research in the form of a Summer Faculty Fellowship, awarded to Allen Nagy. Brian Porter, Bob Schwartz, and Doug Windle (Logicon Technical Services, Inc.) assembled much of the apparatus and wrote the software. Chuck Goodyear (Chuck's Discount Stats) assisted with the statistical analyses. The contributions of these individuals to the concepts and results described in this article are gratefully acknowledged.

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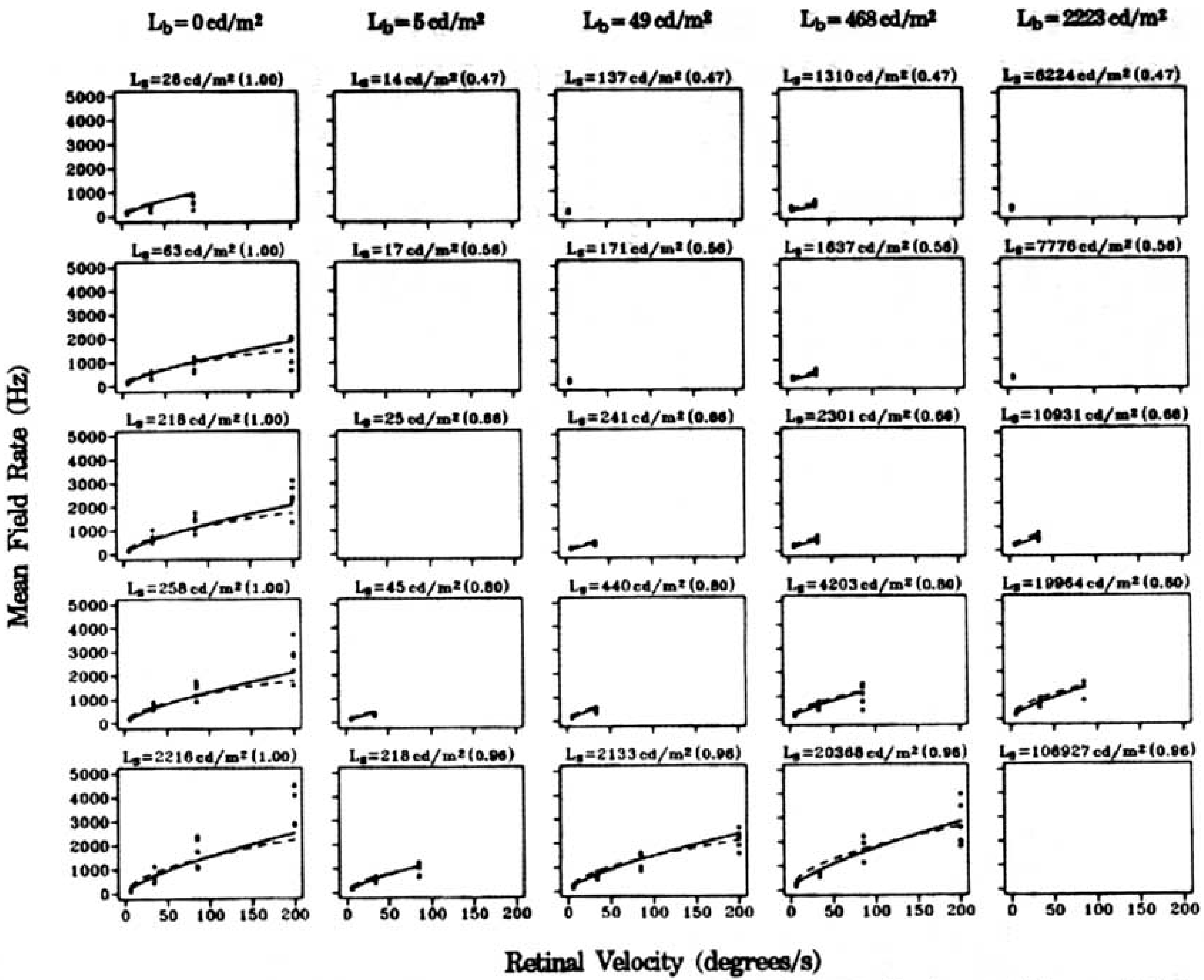

Figure 4. Summary of data and analytic results. L_s is the target luminance, L_b is the background luminance, and the parenthetical values are the resulting luminance modulations. Each dot represents a mean threshold obtained from one of the six participants. The solid lines are the means predicted by Equation 2; dashed lines are the means predicted by Equation 1.